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MANUFACTURING AND TESTING EXPERIENCE WITH DIRECT METAL LASER SINTERING FOR CLOSED CENTRIFUGAL COMPRESSOR IMPELLERS

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ABSTRACT

Direct Metal Laser Sintering (DMLS) is an additive manufacturing process that utilizes a high-powered laser to build up a metal part by selectively melting thin layers of metal powder. This process is attractive for the manufacturing of parts with complex geometry such as closed centrifugal compressor impellers. DMLS allows closed impellers to be made in a single piece and eliminates the shroud joint that results from two-piece manufacturing processes. Using a monolithic impeller can allow higher tip speeds with improved fatigue characteristics compared with two-piece and three-piece designs. Prototype parts can be made more economically than investment casting when considering the tooling costs. Manufacturing costs for DMLS parts are marginally higher than for two-piece machined impellers, but qualification efforts for the braze/weld joint at the cover are circumvented.

The DMLS process introduces several factors that must be considered in the impeller design to achieve a successful build with the proper strength and surface finish. This paper describes the authors' experience with manufacturing and testing multiple closed impeller designs constructed from Inconel 718, 17-4 PH Stainless Steel, and Titanium 6Al-4V. A detailed discussion of design factors and manufacturing experience with a DMLS vendor is included for the various metals. Dimensional, post-test destructive inspection, and material test results are provided showing that the DMLS process can produce an impeller with good dimensional accuracy, surface finish, and material strength. Finally, overspeed test results up to maximum tip speeds of over 1400 ft/s (425 m/s) and aerodynamic performance test results are presented and discussed.

INTRODUCTION

Overview of DMLS Technology

Shellabear and Nyrhilä (2004) define laser-sintering as a method to "manufacture solid parts by solidifying powder-like materials layer-by-layer by exposing the surface of the powder bed with a laser or other energy beam." Correspondingly, they define Direct Metal Laser Sintering (DMLS) as "laser sintering using a metal powder so that metal parts are produced directly in the building process." Though this definition of DMLS is broad, it encompasses the majority of 3D metal printing technologies in the market today.

DMLS is a state-of-the-art technology, but the concept has existed for over 40 years. Pierre Ciraud's patent (1973) describes the creation of solid parts using a beam of energy to solidify powdered material (e.g., plastic or metal powder) onto a substrate material. A few years later, American Ross Housholder (1981) patented a system for fusing particles together in layers. Beginning in 1984, Chuck Hull and his peers continued in the development of numerous patents detailing how three-dimensional (3D) printing, or "stereo-lithography," could be accomplished (1986). The rights to Ciraud's, Housholder's, and Hull's technologies were purchased by several companies seeking different market interests, ultimately resulting in the development of the Sinterstation 2000 from DTM Corp. in 1992 and the EOSINT P 350 from EOS in 1994. These machines initially used plastics, but they were the first commercial Selective Laser sintering (SLS) machines to the market. The capability to manufacture with metals followed quickly when EOS introduced the EOSINT M 250 in 1995, which was initially tested using a bronze-nickel-based powder invented by Nyrhilä and Syrjälä (1990) of Electrolux Rapid Development (ERD).

After the introduction of the EOSINT M 250, the materials and process development evolved quickly through cooperative research between EOS and ERD, increasing the quality and variety of materials available, the rate of build, the accuracy of the build, and improving surface finish. The first parts constructed by DMLS were primarily prototype injection molds, with limited numbers of prototype parts being constructed. Additional 3D metal printing machines from have also been commercialized by other manufacturers, although they use terminology other than DMLS (e.g. Electron Beam Melting, Direct Metal Sintering, or Selective Laser Melting) to describe their processes. The various machines differentiate themselves by varying build volumes, build speed (including multi-beam models), online quality control, and other features.

Currently, there is increasing interest for using DMLS for "rapid manufacturing," such as producing single parts for research-related endeavors or small volume production. With proper heat treatment and Hot Isobaric Press (HIP) processing, when appropriate, manufacturers claim that wrought alloy strength is achievable for DMLS parts. This high strength capability combined with the design flexibility offered by DMLS manufacturing opens up new design space for components, including curved holes, thin sections, light-weight porous shapes (e.g., honeycomb), etc. DMLS is limited by the dimensional envelope of current machines (approximately 12 in, 300 mm, cubed), dimensional accuracy (± 0.005 in, 0.13 mm), surface finish ($R_a \approx 250$ μin, 6 μm), and the speed of manufacturing (e.g., a 200 mm impeller takes several days to build in the machine). Future advances will likely include multiple, more-powerful lasers which will reduce manufacturing time and cost and provide automated surface finish enhancement.

DMLS Design & Manufacturing Process

Starting with a Computer Aided Design (CAD) solid model of the desired part, the engineer or drafter will add machining stock as typical of castings or forgings. This modified CAD model is sent to the DMLS vendor where additional support features specific to the process and machine may be added. The final model is sent to the DMLS machine where the process "grows" the part, layer by layer, from a base plate. Layer size may vary, but typically it is 0.0008-0.0016 in (20-40 μm). Figure 1 illustrates some of the basic stages of the DMLS process to generate a finished part. In addition to being the material that the sintering process will start on, the base plate must also function as a structural support that will maintain the dimensional state of the part while internal stresses develop due to thermal transients inherent in the process – this is particularly important for larger parts.

When the process is complete, the volume of the machine will contain the part, attached to the base plate with the supports, and loose, unsintered powder (Figure 1b). Post-processing of the part begins with removal of the loose powder, a stress-relief heat-treatment so that the part will not deform when it is removed from the base plate, and removal of any other support features. Depending on the application, the part may undergo rough machining and additional heat-treatments and HIP processing (Figure 1c). Finally, when desired, additional processes can be employed to improve surface finish (e.g., extrude-hone of internal passages) or finish machine critical surfaces (Figure 1d).

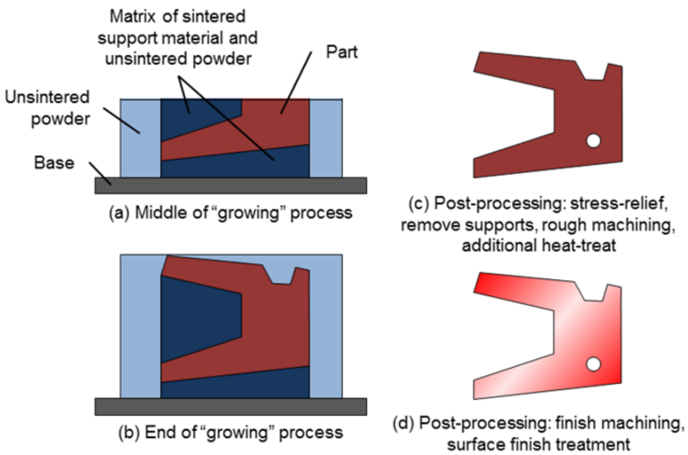

Figure 1. Illustration of DMLS Process

DMLS Applications to Turbomachinery

The use of DMLS for turbomachinery component manufacturing is in its infancy, but it is quickly gaining acceptance. Published applications with significant data are scarce, but documented case studies include both stationary parts, such as a flow straightener for a helicopter gas turbine (Cobalt Chrome MP1), and rotating parts, including a gas turbine wheel (Inconel 718), both shown in Figure 2 (Killian 2013). The gas turbine wheel shown in Figure 2 was reportedly operated at speeds up to 100,000 rpm (size not specified) and inlet temperatures up to 1380 °F (750 °C) prior to being published in 2008. Clay and Tansley (2010) discuss the manufacturing of a 1.57 in (40 mm) open centrifugal compressor impeller from C-263, but no operating data or experience is reported. The authors have also had experience with DMLS manufacturing of closed centrifugal compressor impellers and a closed mixed-flow turbine wheel for a microturbomachine. In this example, the compressor impellers were successfully overspeed tested at tip speeds of 1,140 ft/s (348 m/s) and eventually oversped to failure at a tip speed of 1,403 ft/s (428 m/s). Finally, DMLS has also been used to manufacture and test the heat transfer performance of high temperature gas turbine blades (Cobalt Chrome MP1) in a linear cascade test rig (Mick et al., 2013) with intricate geometry including internal cooling passages with heat transfer enhancement, leading edge film cooling, and pin fin cooling. DMLS blades are expected to lack the creep life of single crystal blades, but they are ideal for development test rigs.

Figure 2. Flow Straightener for Helicopter Gas Turbine Engine (Above) and Gas Turbine Wheel (Below) (Killian 2013)

DMLS for Closed Impeller Manufacturing

Covered impellers can be manufactured in one-, two-, or so-called three-piece configurations. Manufacturing of two- and three-piece covered impellers (hub and shroud are separate, blades are either separate [three-piece] or integral with the hub or shroud [two-piece]) typically involves attaching the separate components using brazing or welding. Five-axis milling of impellers with welded or brazed covers represents the most common manufacturing method, but qualifying this process on a new impeller design can be challenging. Single-piece impellers can be either investment cast for large-volume production or integrally machined, which may not be possible for low-flow designs due to machining access. All of these methods are in current use today, and each approach requires multiple, specialized manufacturing processes that can take significant time. The use of DMLS parts has been used to reduce manufacturing time of long-lead-time parts to reduce schedule and cost risks, which are both key goals of development testing.

Although current DMLS machines are limited to part sizes less than 12 in (300 mm), most impellers for aerodynamic test rigs fall below this size. Since blade fillets may be added to both hub and shroud locations, blade stresses may be reduced to enable higher operating speeds. This feature is useful when testing on gases with a higher speed of sound than the intended process gas (e.g., air compared to natural gas) since higher test speeds are required to achieve the same machine Mach number. Of course, care must be taken when using DMLS parts in prototype testing to ensure that the production geometry is well matched.

In the authors' experience, DMLS manufacturing costs for an 8 in (200 mm) diameter impeller are comparable to a two-piece, 5-axis-milled impeller using Inconel 718. However, brazed aluminum impellers can be manufactured for about 25%

less cost. For single prototype parts, investment casting is nearly twice as expensive as DMLS when tooling costs are considered (based on the authors' experience with parts having similarly complex geometry). Manufacturing time (including all pre-build design iterations and post-build processes) ranged from 8-12 weeks depending on the success of early builds and the vendor's manufacturing schedule.

Test and Manufacturing Program Overview

Samsung Techwin and Southwest Research Institute (SwRI) have collaborated on a multi-year development and test program for closed centrifugal compressor impellers. This program has included the manufacturing and testing of multiple impeller designs, all manufactured via DMLS. A summary of the test program phases and test impellers, including impeller flow coefficients (ϕ), materials, and maximum tip speeds (during overspeed testing), is provided in Table 1.

Since there is little industrial experience with high-speed DMLS impellers in turbomachinery applications, this project also focused on evaluating and validating the manufacturing process and resulting parts. The following sections will discuss these aspects in further detail.

Table 1. DMLS Impeller Testing Program Summary

Phase	Objectives	Impeller Materials	Max Tip Speed
1	Obtain 1st generation impeller performance	ϕ = 0.08 Impeller – 17-4 PH Stainless Steel	NA; Cracked during manufacturing
		ϕ = 0.08 Impeller – Inconel 718	932 ft/s (284 m/s)
		ϕ = 0.11 Impeller – 17-4 PH Stainless Steel	932 ft/s (284 m/s)
2	Obtain 2nd generation impeller performance with volute & multiple seal designs	ϕ = 0.08 Impellers (three variations) – Inconel 718	1321 ft/s (403 m/s)
		ϕ = 0.11 Impellers (three variations) – Inconel 718	1321 ft/s (403 m/s)
		ϕ = 0.11 Impeller – Ti-6Al-4V	NA; Not tested
3	Obtain 2nd generation impeller performance with new volute and diffuser designs	ϕ = 0.08 Impeller – Inconel 718	1411 ft/s (430 m/s)
		ϕ = 0.11 Impeller – Inconel 718	1321 ft/s (403 m/s)

DESIGN CONSIDERATIONS FOR DMLS IMPELLERS

Structural Design – Thermal Considerations

Thermal issues can play a significant role in the overall part design for DMLS. Throughout the manufacturing process, a part is subjected to localized heating and/or varying degrees of thermal transients which cause internal stresses. These stresses can lead to significant changes in dimensional state or material failure if they are not properly managed.

As discussed previously, dimensional state during the build process can be controlled by adding support structures, especially for high aspect ratio features, which constrain a feature until after a stress-relief process (after which the support structures are removed). Alternatively, a certain amount of deflection may be anticipated beforehand – either by previous experience with a similar part or, more precisely, by creating test samples to determine the actual deflection behavior – which allows the prescribed geometry (i.e., CAD model) to be altered such that the final part matches the desired geometry. It may not be unusual to implement both of these approaches for certain parts. In general, there are no published standard rules of thumb when it comes to implementing either of these for a specific application, and manufacturers typically protect the techniques they use to support the features of a given part as proprietary parts of their process.

If thermal stresses are not well managed, the part may experience yielding or fracture during the manufacturing process. In particular, cases where there are "thick" and "thin" material sections adjacent to each other (e.g., blades between a centrifugal compressor hub and shroud) can accentuate these problems. In essence, the different thermal capacitances or heat capacities of the adjacent materials can lead to dissimilar heating or cooling rates that may stress areas of the part beyond the capability of the material. In this test program, the team experienced such a failure during the manufacturing of the 1st generation 0.08 ϕ impeller from 17-4 PH stainless steel with H900 heat-treat condition. Figure 3 shows a photograph of cracks that developed at the blade leading edge near the shroud fillet. In this case, the cracks developed during the liquid quench process of the heat treatment due to the large difference in relative cooling rates between the blade and hub.

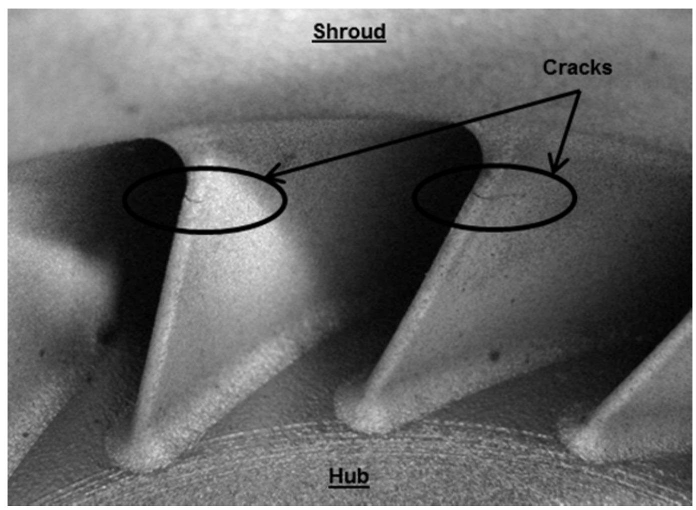

Figure 3. Cracks at Blade Leading Edge Due to Heat Treatment of 1st Generation 17-4 PH Stainless Steel Impeller

Rather than try to remake the impeller from the same material and modify the heat-treat process, the manufacturer recommended remaking the impeller from Inconel 718, which, from their experience, was not expected to have the same complications since it only required a gas quench process. Alternatively, the hub could have been redesigned with a thinner cross-section (thus, lower thermal capacitance), but that would have required additional analysis iterations which would have compromised the test schedule. This particular impeller was remade from Inconel 718 and resulted in a crack-free part.

In Phase 2, a duplicate of one of the 2nd generation 0.11 ϕ impellers was manufactured from Ti-6Al-4V in order to evaluate the manufacturing experience with the new material. Due to its superior density-to-strength ratio, titanium was expected to permit operation at higher test speeds without yielding. To avoid developing large thermal stresses during manufacturing, the hub was redesigned to reduce the thermal capacitance sufficiently so that the part would not crack while "growing", yet still maintain the structural integrity required for the high-speed operation. After several iterations, a hollowed, ribbed hub design shown in Figure 4 was determined to be sufficient for avoiding thermally-induced cracks during the build process.

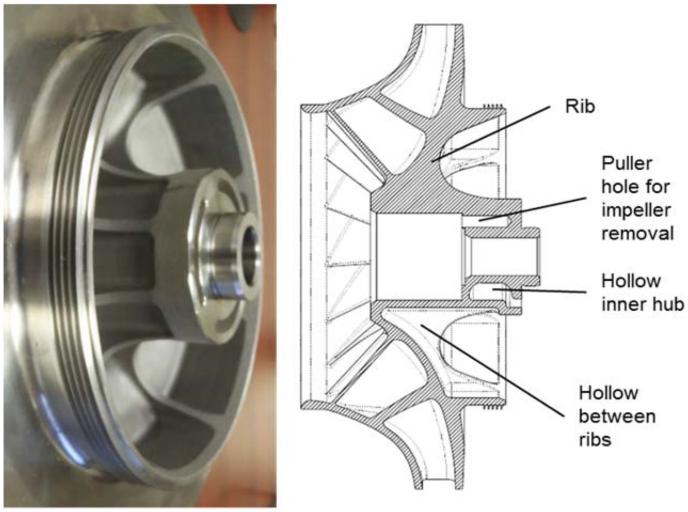

Figure 4. Thinner Cross-Section Hub Design Required for Titanium Impeller

Structural Design – Finite Element Analysis

Finite element models were constructed and analyzed for each impeller in order to ensure safe operation up to the maximum test speed, and during overspeed testing, without failure. Additionally, Finite Element Analysis (FEA) results were applied to size hub and eye seal clearances so that leakage would be as low as possible while minimizing the possibility of rubbing at maximum speed. In general, these analyses did not require special treatment for the DMLS manufacturing process. Most analyses were based on linear-elastic material properties (provided by the DMLS manufacturer); however, nonlinear elastic-plastic analyses were also conducted for some of the highest-stressed test cases in order to determine the extent and location of plastic deformation. This section briefly summarizes the various FEA investigations performed for two of the impellers at their most extreme operating conditions.

First, elastic-plastic analysis results are shown for the 2nd generation 0.08 ϕ impeller at its overspeed condition (1,411 ft/s, 430 m/s). The commercial FEA software used (ANSYS Workbench™ 2013) can accommodate nonlinear material properties for performing an elastic-plastic analysis, and a bilinear material stress-strain curve was utilized. Since the DMLS vendor could only provide density and yield strength (163 ksi, 1.12 GPa), the elastic modulus, post-yield modulus, and Poisson's ratio were obtained from (Brown 2002). A 1/16 sector model was analyzed with 227,218 elements and 381,213 nodes with high mesh density enforced at the fillet locations.

The equivalent stress and plastic strain fields at the overspeed condition are shown in Figure 5 and Figure 6, respectively. Although the impeller is predicted to yield, the yielding is relatively low (0.4%) and localized to the fillets and some small areas in the shroud, with no yielding in the hub. Thus, the design was considered to be acceptable for the desired speed.

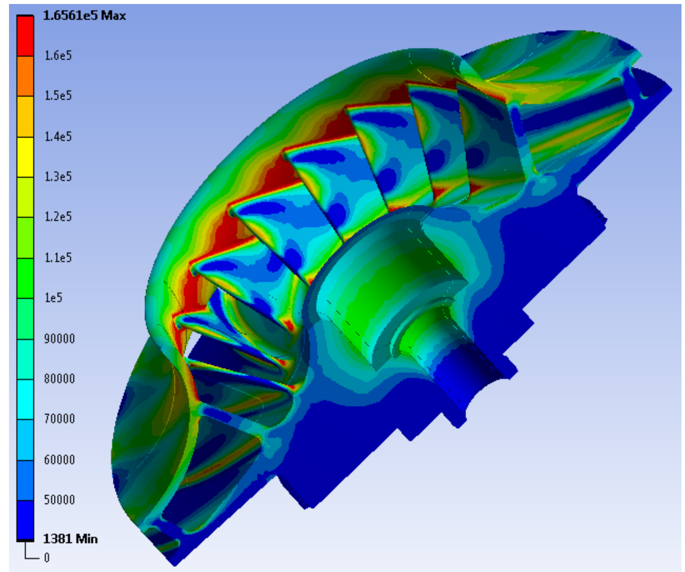

Figure 5. Elastic-Plastic Analysis Stress Results (psi) for 2nd Generation 0.08 ϕ Impeller, Overspeed Condition

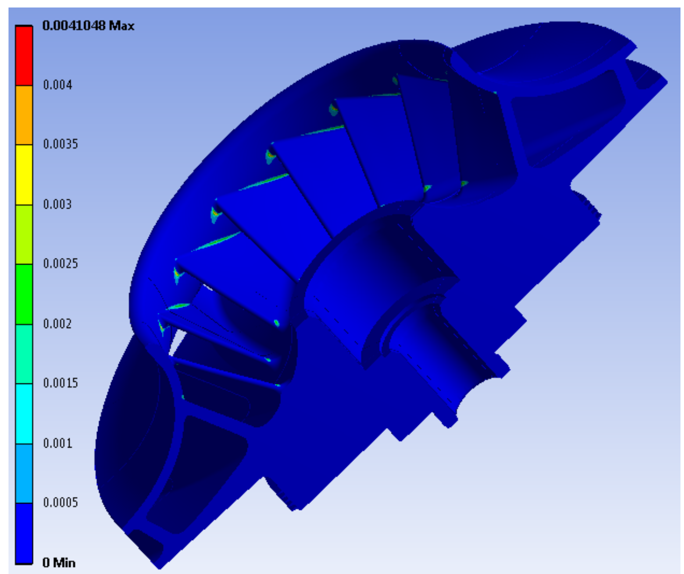

Figure 6. Elastic-Plastic Analysis Plastic Strain Results for 2nd Generation 0.08 ϕ Impeller, Overspeed Condition

An elastic analysis was also performed on the 2nd generation 0.11 ϕ impeller made from Ti-6Al-4V in order to quantify the effects of the ribbed hub on operating deflections and stresses at the maximum operating speed. Figure 7 shows the Von Mises stress field in the impeller hub (inset image is a close-up of one of the ribs). The highest stresses are in the material adjacent to the rib fillet followed by the area in the rib at the minimum rib height. The highest stresses are between 140-150 ksi (0.97-1.0 GPa), which is very close to the yield strength, so yielding during the overspeed test would be expected (including within the ribs in the hub). The ribbed hub supports were also found to cause a circumferential variation of ±0.0011 in (±0.03 mm) in radial deflection of the hub seal. For these reasons, the Inconel 718 impeller with identical flow path geometry was tested rather than the Titanium part. These results indicate that future designs of Titanium impellers for DMLS manufacturing must carefully consider these tradeoffs between manufacturability and operating performance.

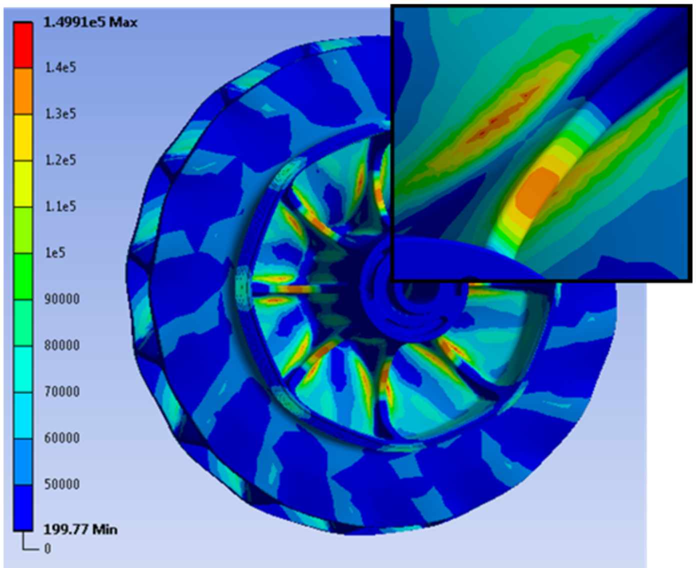

Figure 7. 2nd Generation 0.11 ϕ, Ti-6Al-4V Impeller – Von Mises Stress (psi) at 37,830 rpm

Aerodynamic Design

The aerodynamic design of a centrifugal impeller is always constrained by manufacturing requirements and limitations. This is particularly true for covered impellers. In the case of impellers manufactured with a brazed or welded cover, the maximum tip speed, U_2, is limited by the strength of the joint. Therefore covered impellers are typically limited to low pressure ratio applications. As previously mentioned, single-piece impellers manufactured by DMLS may include blade fillets at both hub and shroud locations, so lower stress concentrations would allow higher operating speeds.

For this test program two different impellers were designed and tested. The first impeller was designed at a flow coefficient $\phi = 0.08$ and the second at $\phi = 0.11$. Both impellers were designed to run at a peak machine Mach number, M_{U2}, of 1.0 and an isentropic head coefficient, ψ, slightly greater than 1.0.

The impellers used in this testing were designed to allow for two-piece manufacturing methods, with a 5-axis-milled impeller and backface mated with a welded shroud. Accordingly, the blades are a ruled element design for flank milling. The impellers were designed with 16 main blades with 40-50 degrees of backsweep and no splitters. Relatively thick blades were maintained at the shroud to leave sufficient material for welding.

Single-piece DMLS-manufactured impellers allow for similar design freedom available with casting, but they can be manufactured economically on a small scale. Although the impeller designs were suitable for two-piece manufacturing for this development test program, specifically designing for DMLS manufacturing would make it practical to design complex bowed, or 3D blade profiles that can be produced without additional expense that would be incurred in a milled design. Additionally, the increased strength of a single-piece impeller allows for a significant increase in the expected strength and life of each impeller. This additional strength may be exploited in future designs to design to higher machine Mach numbers. Efficient operation at higher Mach number may allow for the design of machines that use fewer stages and are mechanically simpler.

Summary

By the nature of the process, DMLS introduces varying degrees localized heating and/or thermal transients, which cause internal stresses in a part during manufacture, which may result in dimensional inaccuracy or material failure. Countering this aspect requires considerations in the part design which can minimize differences in thermal capacitance (i.e., avoid close proximity of thick and thin features which have different heating or cooling rates), addition of support structures to the part that may be removed after stress-relief, and other special considerations required for the particular material used. There are no general rules of thumb to implement either of these approaches, and manufacturers typically have their own proprietary methods which have been developed over time with experience.

Other than the special manufacturing considerations, utilizing FEA, both linear elastic and nonlinear elastic-plastic, was important to come up with impeller designs that were structurally sound up to the overspeed condition. While these analyses are not necessarily unique to impellers manufactured by DMLS, confidence was gained pertaining to their applicability to DMLS materials. Similarly, the aerodynamic design process was not unique for DMLS manufacture, but geometric features not possible with other manufacturing methods (e.g., blade fillets on hub and shroud, more complex blade shapes, etc.), although not necessarily implemented in this test program, could be a path to economic small-scale, high performance impeller designs.

DMLS IMPELLER MANUFACTURING AND INSPECTIONS

Photos of the manufactured impellers are provided in Figure 8 and Figure 9 for 1st generation and 2nd generation impellers, respectively. The inset image in Figure 9 shows artifacts of the DMLS support structure near the hub side fillet that were not completely removed by the extrude-hone process. These photos highlight the significant improvement in surface finish from 1st to 2nd generation impellers due to the DMLS vendor's improvements in executing the extrude-hone process, namely using a more appropriate abrasive grit size.

Figure 8. 1st Generation Impeller

Figure 9. 2nd Generation Inconel Impeller

Detailed dimensional inspections were performed on critical surfaces of most of the impellers (such as seal diameters, etc.), where possible, prior to testing. Most critical non-flowpath surfaces were post-machined to match specified tolerances, but the exit flow path width accuracy and flow path surface roughness were largely a result of the DMLS and extrude-hone processes. The inspection results, summarized in Table 2, show that the DMLS process was able to meet specified dimensions on non-machined surfaces within 0.015 in (0.38 mm) at the worst case and within 0.003-0.005 in (0.08-0.13 mm) on the most accurate builds. It is noted that the 'a', 'b', and 'c' versions of the 2nd generation impellers all share the same hub geometry. Significant accuracy improvements in impeller exit width were achieved upon successive builds due to calibration of the build process. Although surface roughness was not measured for the Phase 1 impellers, there was a significant improvement in surface roughness from Phase 1 to Phase 2 through fine-tuning of the extrude hone process.

Table 2. Dimensional Accuracy of Manufactured Impellers

Impeller	Impeller Exit Width Accuracy (inches)	Flow Path Surface Roughness (R_a)
1st Generation 0.08 ϕ Impeller	+0.011	NA
1st Generation 0.11 ϕ Impeller	NA	NA
2nd Generation 0.08 ϕ Impeller Variation 'a'	-0.015 to -0.010	63-125
2nd Generation 0.08 ϕ Impeller Variation 'b'	-0.011 to -0.005	7-32
2nd Generation 0.08 ϕ Impeller Variation 'c'	-0.005 to +0.000	16
2nd Generation 0.11 ϕ Impeller Variation 'a'	-0.014 to -0.012	63-125
2nd Generation 0.11 ϕ Impeller Variation 'b'	-0.005	63-125
2nd Generation 0.11 ϕ Impeller Variation 'c'	-0.003	16-92

A fluorescent penetrant inspection was performed on one of the 2nd generation impellers immediately after manufacturing but before any balance or overspeed work was performed. The inspection revealed numerous areas of pitting or crack-like indications around the blades, which was considered by the DMLS vendor to be normal for a typical DMLS part. After overspeed testing, FPI was not performed a second time, but critical dimensions were measured again in order to ensure that significant plastic deformation did not occur.

Proper understanding of the material characteristics of components manufactured through DMLS is critical to achieving a successful structural design. Static characteristics are important to prevent overload-related fractures. To assess the risk for overload rupture and/or plastic deformation of critical dimensions it is essential to have nominal and minimum yield strength and ultimate tensile strength. Dynamic characteristics are important to prevent fatigue-related fractures. Fatigue-related fractures take one of two forms: low-cycle and high-cycle. Low-cycle fatigue fractures are mainly the result of start-stop cycles of the turbomachine and therefore depend upon the duty cycle of the machine. High-cycle fatigue fractures result from dynamic excitations in the flow stream and resonance characteristics of the impeller. Experimentally-derived S/N diagrams allow the ability to design based upon fatigue life.

Without access to commercially-available material properties, a material assessment program was initiated to support transition of the DMLS impellers into the market. Lind et al. (2003) provide some limited bronze and steel data, but additional data were required, particularly for the Inconel 718 impellers. After aerodynamic performance testing, one of the 2nd generation Inconel impellers was sectioned and tested to evaluate material microstructure, tensile strength, and fatigue strength.

Figure 10 shows two sections of the impeller and specific planes where the part was examined. Another view of a sectioned impeller is shown in Figure 11, showing that the part has good overall solidity and minimal porosity (at least on the macro scale). Figure 12 shows a 50× magnification of the shroud fillet area. It can be seen that the surface is rougher than a machined part. Care must be taken to ensure that post-processing delivers a smooth flow path with a consistent surface finish to avoid stress concentrations that could develop on the surface.

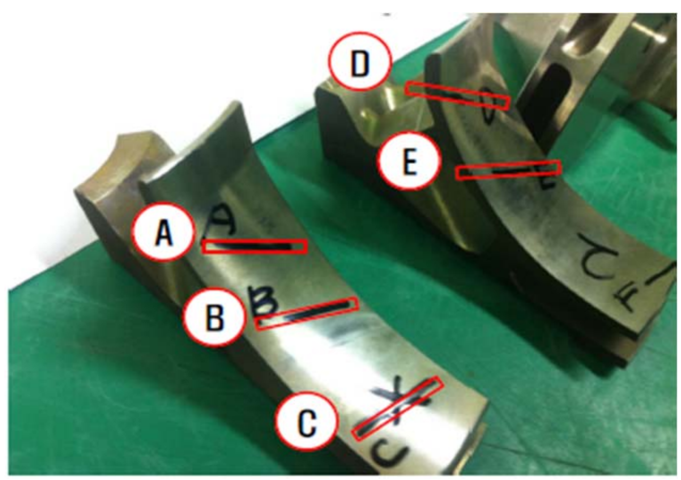

Figure 10. Sections of 2nd Generation DMLS Shrouded Impeller Being Cut for Inspection

Figure 11. Section View of 2nd Generation DMLS Shrouded Impeller Indicating Good Solidity

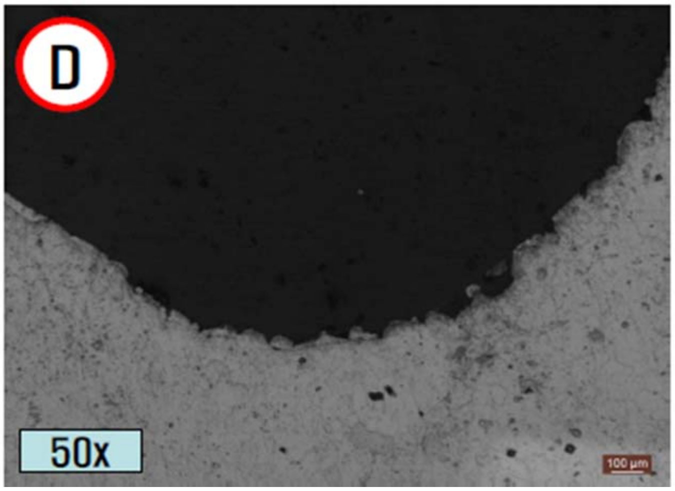

Figure 12. Magnified View of Fillet Region Between Impeller Blade and Shroud

A microscopic examination was performed to compare the sectioned impeller parts with a sample of wrought Inconel 718 (AMS5662) that was heat treated similarly to the DMLS part, but did not undergo a HIP process. The examination results, shown in Figure 13, reveal a different grain structure for the DMLS part compared to the wrought sample. One concern with the use of DMLS is the presence of voids in the material. Voids may develop as the sintering process is influenced by particle size. Figure 14 shows that micro-porosity did exist in the DMLS material specimens examined, but that the porosity level is limited to 20μm or less.

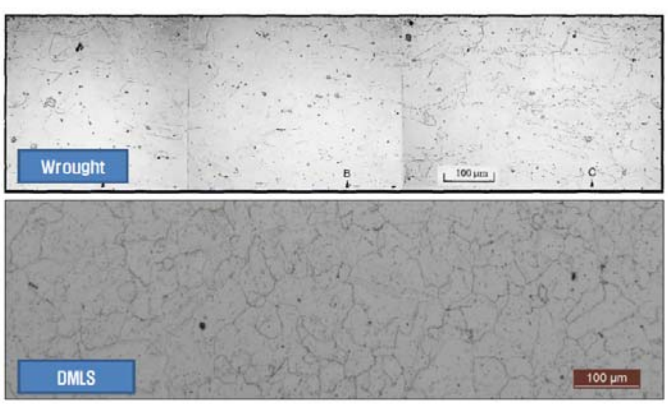

Figure 13. Comparison of Grain Size Between Wrought Inconel 718 and DMLS Inconel 718

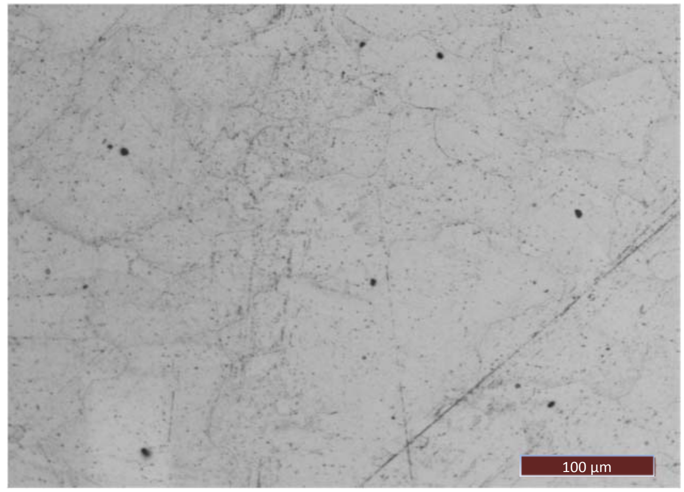

Figure 14. Magnification of DMLS Inconel 718 Sample Showing Micro-Porosity

Since the grain structure for DMLS Inconel 718 is different than the wrought Inconel 718, it is expected that differences in key material characteristics will be present. Table 3 compares hardness and ultimate tensile strength of DMLS and wrought Inconel 718 parts based upon a limited sample (5 hardness tests and two ultimate tensile strength tests).

Table 3. Comparison of Static Material Characteristics of Wrought Inconel 718 and DMLS Inconel 718

Parameter	DMLS Sample Relative to Wrought Material
Grain Size	Increased
Hardness	Increased 37%
Ultimate Tensile Strength	Increased 4.2%

With the presence of micro-porosities and increased material hardness one natural concern is the fatigue life of the DMLS material. Increased material hardness and ultimate tensile strength for similar materials are indications that components may have a lower fatigue life margin. Fatigue tests comparing the strength of wrought and DMLS material samples at two load amplitudes are shown in Table 4.

Table 4. Comparison of Fatigue Strengths of Wrought Inconel 718 and DMLS Inconel 718

Max Strength, ksi (MPa)	Fatigue Strength of DMLS part relative to wrought Material
159.5 (1,100)	72%
145.0 (1,000)	63%

These results indicate that some fatigue strength reduction may be present in DMLS parts relative to wrought materials. Because DMLS is still a relatively young technology compared to casting or other manufacturing processes, only limited material information is commercially available to support the design process. For prototype testing, this should not be a concern, but additional testing may be required for production applications in order to determine statistically significant variations of the material properties and acceptable design margins.

DMLS IMPELLER AERODYNAMIC TESTING

Test Rig Overview

The impeller aerodynamic testing was accomplished in the Single Stage Test Rig (SSTR) at Southwest Research Institute in San Antonio, TX. This test rig consists of a 200 hp (150 kW) (at 3,600 rpm) electric motor with variable speed drive, a speed-increasing gearbox (11:1 ratio), and a high-speed spindle rotor assembly that can operate up to 40,000 rpm. The test impeller is mounted to the spindle rotor assembly with a precision pilot fit and a tie bolt, which allows the impellers to be installed and removed without disassembly of the rotor shaft, bearings, seals, and coupling, greatly simplifying configuration changes. The rotating and stationary assemblies are mounted on centerline risers which maintain alignment even for dissimilar thermal growths in the test and drive sections. Flow rate is measured at the inlet to the SSTR using a calibrated bellmouth Venturi, and throttling takes place at the discharge via a control valve. Inlet and exit pipe dimensions and temperature and pressure measurement locations are configured such that they satisfy distance requirements for ASME PTC-10 (1997) for compressor performance and ASME PTC-19.5 (2004) for flow measurement. The SSTR housing is insulated to minimize heat transfer to the environment. Figure 15 shows the various features of the SSTR; and the cross-section depicts a simple collector configuration for the 1st generation 0.11 ϕ impeller.

The test rig is able to accommodate various impeller geometries by manufacturing of custom shroud side (and hub side, if necessary) diffuser pieces. Custom seal inserts (both hub and eye seals) and transition pieces are also manufactured for each impeller. In this manner, various seal configurations can be tested. The diffuser gap and alignment can be set on both sides via axial and angular adjustment of the stator plate (hub side) and shimming of the shroud side diffuser piece against the front cover plate. The rig is also ideal for testing various inlet guide vane, diffuser, volute and/or return channel geometries economically due to its ease of access and low pressure design. Notably, these components have been successfully manufactured and tested using other rapid additive manufacturing techniques besides DMLS: SLS with Duraform HST material for the inlet guide vane assemblies (Figure **16**a) and 3D-printed sand casting molds for aluminum volutes (Figure **16**b).

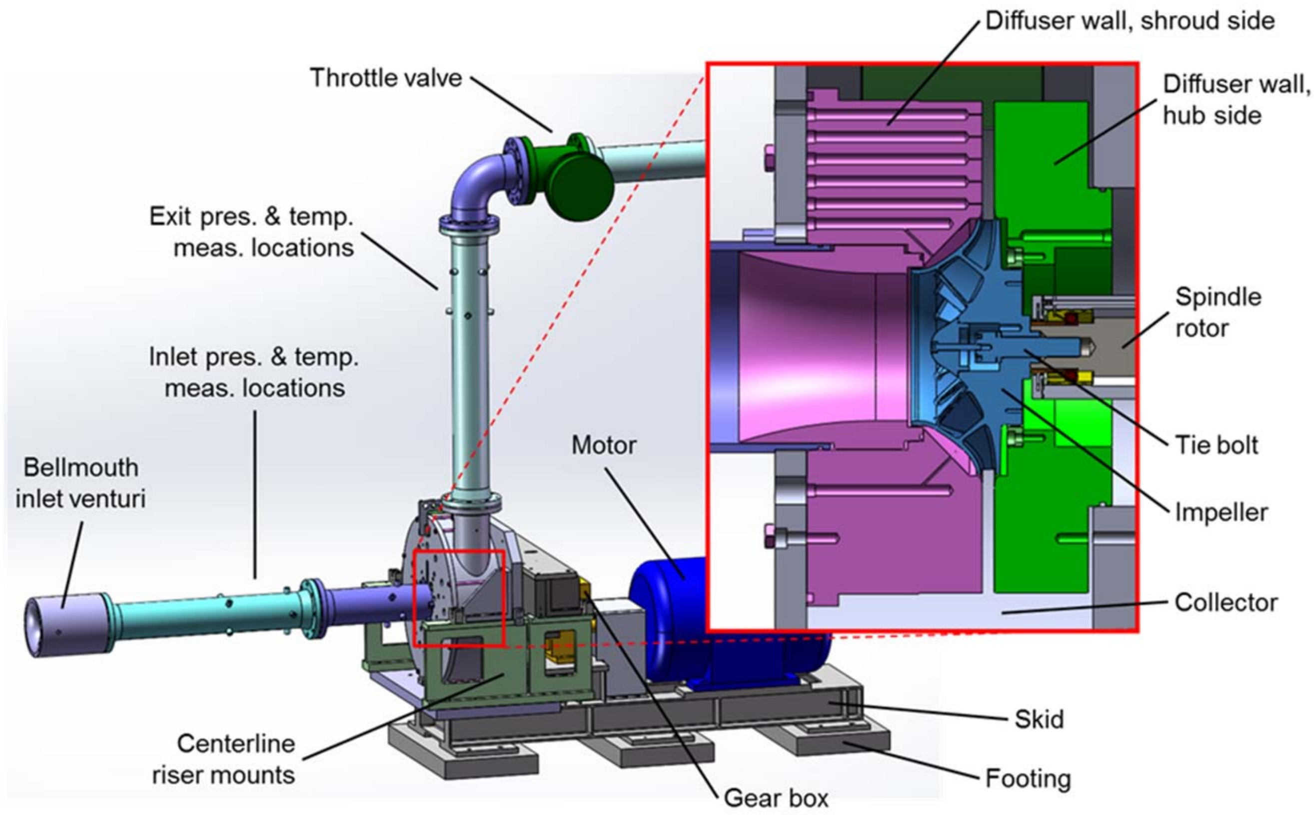

Figure 15. SSTR Layout – Simple Collector Configuration

(a) (b)

Figure 16. (a) Selective Laser Sintered Inlet Guide Vane Assemblies and (b) 3D Printed Sand Cast Volute Installed in SSTR

Aerodynamic Test Results

After a seal wear-in procedure, each of the tested impellers was operated in the test rig at multiple speeds from choke to surge/stall. The maximum tested speeds were 15% lower than overspeed tests shown in Table 1 and corresponded to a machine Mach number M_{U2} of 1.0. Total test times for the various impellers range from approximately 12 hours to 36 hours. No mechanical issues were experienced with any of the impellers during testing.

Total-to-total stage performance was calculated for each impeller using static pressure and total temperature measurements in the inlet and exit piping in accordance with ASME PTC-10 guidelines. Multiple speed lines were obtained for each impeller by operating at 8-9 points across the map from choke to stall/surge. At each operating point, the compressor was operated at steady-state while calculated efficiency was monitored. Once the efficiency reached a steady value, a data snapshot was taken by acquiring 20 seconds of raw data, averaging it, and using the averaged values in subsequent performance calculations. Moist air properties (using the measured relative humidity at the rig inlet) were obtained using equations of state for moist air in the NIST REFPROP program (Lemmon et al. 2010).

Dimensionless performance results for the 2nd Generation 0.08 ϕ impeller tests are compared with meanline predicted performance in Figure 17 and Figure 18, where efficiency at each point is normalized with respect to the maximum predicted efficiency. These figures indicate a good match overall between test and predictions. There are minor discrepancies in efficiency and head coefficient, but these cannot be attributed to the DMLS process without comparison with test data from a two-piece impeller with identical geometry. The flow coefficients at peak efficiency and choke are also lower than predicted values (particularly in choke), which may be due to the impeller exit passage width being lower than specified for this particular impeller.

A careful review of the test data showed that peak efficiency was measured at a slightly lower flow than expected. The authors believe that this was due in part to the exit width of the DMLS parts being slightly undersized. It is also possible that the larger passage roughness led to some reduction in flow and head compared to a typical machined impeller.

Performance data for other impellers is not shown, but follows similar trends.

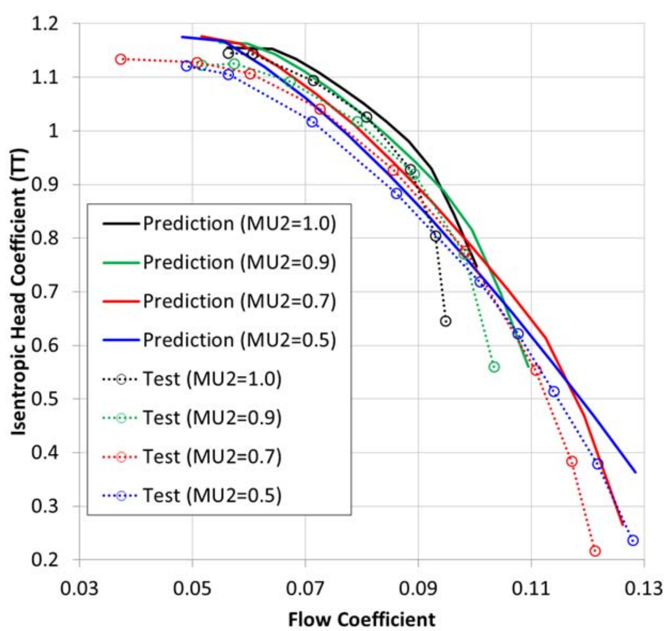

Figure 17. Comparison of Predicted and Tested Head vs. Flow Coefficient

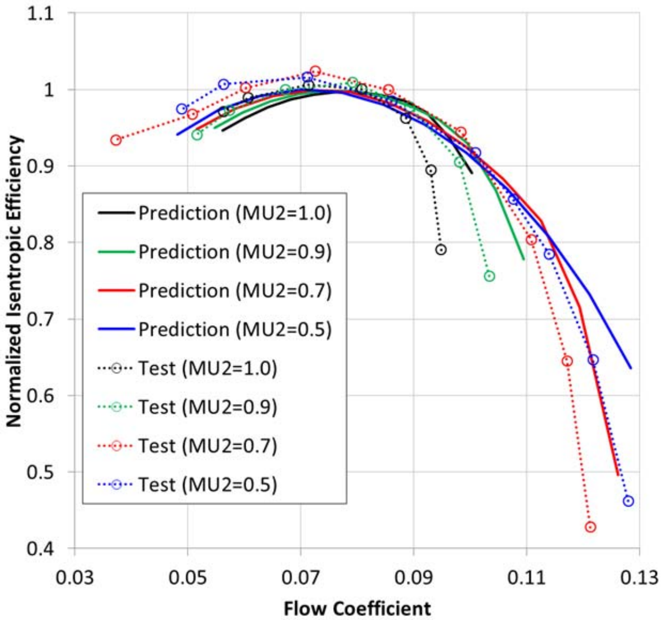

Figure 18. Comparison of Predicted and Tested Normalized Isentropic Efficiency vs. Flow Coefficient

CONCLUSIONS

DMLS is an attractive option for test rig articles due to its design flexibility and reasonable turnaround times, and may be attractive for production machinery since the process allows for one-piece parts with reduced stresses and potentially higher operating speeds.

The authors' experience over several years of development testing has shown that the DMLS process has been successful for manufacturing test prototypes out of Inconel 718, 17-4 PH Stainless Steel, and Ti-6Al-4V, but that certain characteristics of the DMLS process must be accounted for in the impeller design. These characteristics include thermal stresses encountered during the build and heat treat processes, proper surface finishing, and calibration of the build process over multiple builds for best tolerances. Some of these considerations rely on the experience and/or proprietary techniques of the manufacturer.

Impeller analysis and test results have shown that the tested DMLS impellers possess acceptable mechanical characteristics, even when some localized material yielding is experienced during overspeed testing. Pre-test and post-test inspections indicate that acceptable dimensional tolerances and surface finish were achieved, particularly once the build and extrude hone processes were calibrated over multiple builds. Sectioned views of the parts indicate good solidity throughout the part, but a rougher surface near the fillet region of the blades. While this is not a concern for prototype testing, additional evaluation should be performed for production designs in order to ensure adequate fatigue life.

Since a machined impeller of identical nominal geometry was not tested for any of the DMLS impellers, it is not possible to quantify the effects of DMLS manufacturing on impeller performance directly. However, test data indicate that measured head coefficient, flow coefficient, and efficiency of the DMLS impellers are very close to predicted values. Future work in the use of DMLS for manufacturing rotating parts in production machinery will likely include optimizing impeller designs specifically for the DMLS process, improvement of surface finish technologies and tolerances, introduction of new materials, and characterization of fatigue performance of DMLS parts.

NOMENCLATURE

Symbols

ϕ	Flow Coefficient [-]
ψ	Isentropic Head Coefficient [-]
η	Isentropic Efficiency [-]
M_{U2}	Machine Mach Number [-]
U_2	Tip Speed [LT^{-1}]

Acronyms

CAD	Computer Aided Design
DMLS	Direct Metal Laser Sintering
FEA	Finite Element Analysis
SLS	Selective Laser Sintering
SSTR	Single Stage Test Rig
SwRI	Southwest Research Institute

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